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Vibration Energy Harvesting with PZT Micro Device

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Abstract

A micro power generator harvesting vibration energy by resonant inertial oscillation of a piezoelectric laminated cantilever with proof mass was designed, fabricated, and characterized. The active part with 2 µm thick PZT on 5 µm silicon was equipped with interdigitated electrodes to achieve higher voltages. A coupling constant k^2=5% was derived from the difference in resonance frequencies at low and high impedance. At optimal load impedance, a voltage of 1.6 V and an output power of 1.4 µW was measured with a 0.8x1.2 mm cantilever having an active area of 0.8x0.4 mm, excited with 2g at 870 Hz.

Keywords: Micropower generator; vibration harvesting; PZT thin film; piezoelectricity

1. Introduction

During recent years, energy harvesting from vibration and motion sources has attracted much interest, particular as micro power sources. The main applications are wireless communication and sensors. Supply powers of < 100 µW are sufficient to operate wireless nodes in the silent mode. The duty cycle can be quite small, so that mW supply levels already enable some autonomy. Motion and vibration are the most versatile and ubiquitous ambient energy source available, if light harvesting is excluded by the application.[1] The mechanical to electrical energy transformation is most efficiently done by piezoelectric materials. In a micro generator version, an elastic structure containing a piezoelectric film is strained by coupling to the external vibration by means of induced inertial motion at resonance. Such sources must match their resonance frequency to the external vibration spectrum. Vibrations from machinery usually have a frequency of around100 Hz, i.e. very low for micro systems, as resonant frequencies tend to increase with shrinking dimensions and masses. A useful soft elastic body is a rather thin cantilever with a large mass.

The energy transformed from mechanical to an electrical form is proportional to the piezoelectric coupling k^2, which in the case of MEMS structures is not the material constant of the piezoelectric layer, but includes the rigidities of the other elastic materials involved in the deformation, and the relative dimensions, including the volume fraction of the piezoelectric material in the total elastic body.[2] During vibration of the cantilever, the extraction of electrical energy manifests similar as friction in the cantilever motion.[3] For this reason, the coupling

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coefficient k^2 must be close to the mechanical damping ratio for optimal harvesting. In case the cantilever is operated in air, Q-factors are typically around 50. The coupling factor must thus amount to some percent.

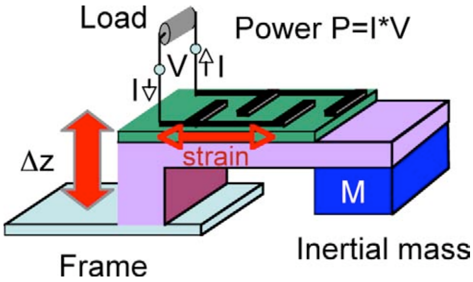


Figure 1: Schematic structure and operation principle of piezoelectric laminated cantilever for harvesting vibration energy coupled in through the vibration of the frame.

An important point in thin film piezoelectric harvesters is the choice of the electrode type. PZT parallel plate capacitors exhibit a large capacitance, resulting in low voltage outputs. One has to keep in mind that vibration harvesting devices have an AC current output that needs to be rectified for energy storage in a battery. All such rectifying semiconductor devices need at least 500 mV for efficient rectification, even when using charge transfer switches for voltage multiplication.[1,4] As a consequence, it is much better to use interdigitated electrodes for harvesting with high permittivity piezoelectrics, because the separation between the fingers is larger than the film thickness. The price to pay is to invest more into poling procedures. Such devices were first demonstrated by Kim and coworkers.[5] They report 1.0 μW and 2.4 V at 14 kHz and 14 nm amplitude with a beam of roughly 200*150 μm. The high frequency of 14 kHz is quite unlikely to be useful for harvesting. The frequency needs to be lowered. In an earlier work we reported on a device vibrating at 900 Hz, yielding 0.85 μW and 1.8 V at 2 g acceleration.[6] The present paper reports on an improvement of this device.

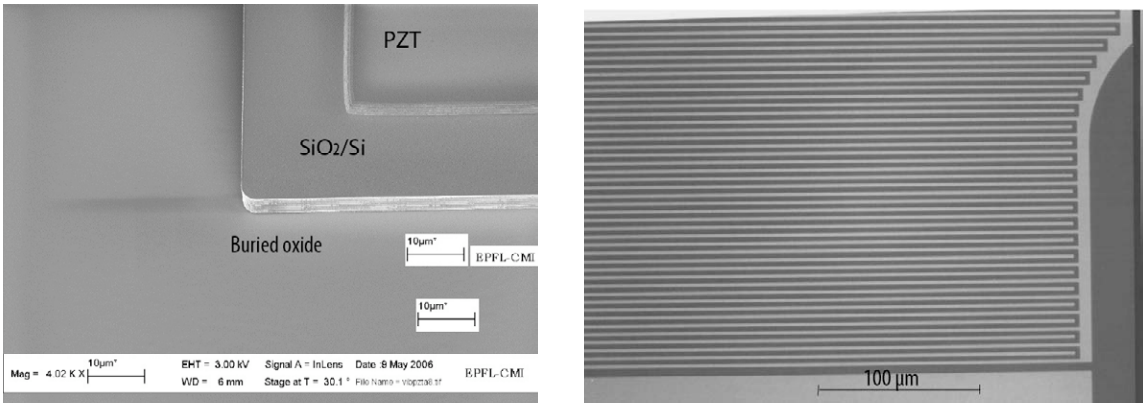
2. Fabrication

2.1. PZT thin film deposition

The quality of PZT thin films integrated on silicon devices has advanced very much during the last 15 years.[7] Important for flexural structures is to achieve a high density, because porosity reduces the film rigidity and thus the piezoelectric stress imposed to the flexural structure in case of actuators, or reduces the piezoelectric charge in case of sensors. To date, the highest quality films for MEMS purpose is achieved with sol-gel processes.[8, 9] Sputtered films still need further improvement, and MOCVD films do not seem to be available for MEMS fabrication. In this work, PZT was not deposited onto a Pt bottom electrode as in most previous works. In order to apply an ID electrode, PZT must be deposited onto an insulating layer, i.e. onto thermal oxide in this case. To avoid diffusion of Pb into the SiO_2, a thin TiO_2 barrier layer was first deposited by sputtering. The 2 μm thick PZT films was grown in 8 annealing sequences with crystallization anneals at 650 °C, whereby each 250 nm sub-layer was obtained from 4 spinning and pyrolysis steps (as in [8,10]). Whereas the (001)-texture control for optimal PZT properties is well mastered for growth on Pt(111) thin films by suitable seed layers [11], this art is not so much advanced yet for growth on SiO_2. In addition, it is not shown yet whether the (001) orientation would be optimal for ID electrodes. The obtained PZT film showed a mixed orientation.

2.2. Device fabrication

The idea as to use silicon from the wafer as inertial mass, like in an earlier work on accelerometers.[12] The essential improvement is the use of SOI wafers for a defined beam thickness, and a much more optimal PZT/Si thickness ratio that should be close to 2 for a good coupling coefficient.[2] In the present work, the device layer thickness was 5 μm, on top of which an oxide layer of 1μm was grown for stress compensation of PZT.[10] Together with the PZT and oxide, the device layer defined the thickness of the flexible part of the cantilever into which the bending is concentrated. After PZT deposition, 0.39 µm thick Au/Cr electrodes were deposited by evaporation and structured by lift-off. The ID electrode fingers were 4 µm thick, the gap between fingers amounted to 6 µm. The ID electrode (fig. 2b) occupied the first 400 µm, i.e. the active part, of the 1.2 mm long and 800 µm wide cantilever. The remaining length was used for the seismic mass formed by the complete wafer thickness below this area of 800x800 µm. After patterning PZT, thermal oxide and silicon at the front side (fig. 2a), the cantilevers were liberated from the backside, removing the silicon from the handle wafer down to the buried oxide below the active part.

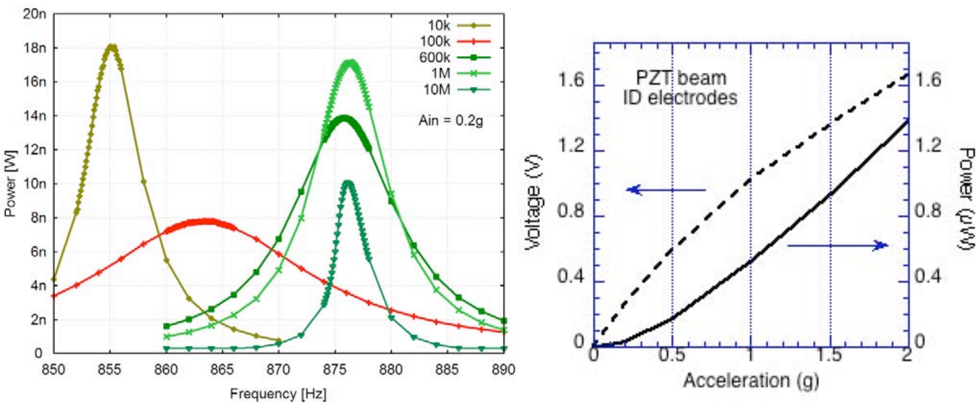


(a) (b)

Figure 2: Top view after patterning the device side of the wafer: (a) The end edge of the seismic mass; (b) The active part of the cantilever with the interdigitated electrode.

3. Results and discussion

After packaging on a PCB board, and poling of the PZT by means of the ID electrodes, the device was mounted on a vibration stage and evaluated as a function of frequency and resistive load. The measured power depended strongly on the load, showing two peaks (fig. 3a). At low resistance, the peak power is observed at resonance (f_r=855 Hz), at high resistance the peak power is observed at anti-resonance (f_a=877 Hz). The difference between the two peaks reveals the coupling constant, amounting to about $k^2=2(f_a-f_r)/f_r$, calculated as 5.0 %. This good value shows that the PZT with ID electrode is as good as optimal textured PZT in parallel plate geometry.[13]



(a) (b)

Figure 3: Power output as a function of frequency for various load resistances (a), and voltage and power output as a function of acceleration measured at the antiresonance.

The measured voltages were suitable for rectifier requirements when the generator was operated at antiresonance. The required 0.5 V were achieved at 0.4 g acceleration. The µW power output was reached at 1.5 g (fig. 3b). Normalizing the output power per g and active area, a value of 220 µW/g/cm^2 is obtained. Such a value thus would be sufficient for powering a wireless node in the silent state. The question is of course, how to get the vibration level of 1 g, or a vibration amplitude of 0.3 μm (870 Hz). Suitable frequencies of machinery, tools, motors, cars, etc. are rather found at frequencies around or below 100 Hz (6000 rpm). There is thus a challenge to design a micro device for such low frequencies that exhibits the necessary robustness. In a recent work,[14] it was proposed to use spiral structures as soft springs.

4. Conclusions

A micro device for vibration energy harvesting based on a piezoelectric thin film was successfully fabricated and tested. The interdigitated electrode system yielded as good piezoelectric couplings constants as optimized parallel plate structures. The voltage and power range was compatible with requirements for practical applications. Future works will concentrate on improving PZT for ID electrode systems, and the geometry for lower vibration frequencies.

Acknowledgements

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